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ORIGINAL PAPER

Application of fractal theory in assessing soil aggregates in Indian tropical ecosystems

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Abstract: Soil aggregation varies according to climatic and management factors, and is difficult to measure because of irregular shapes and sizes of soil aggregates. We applied fractal theory to assess soil aggregation as affected by (1) land use change from forest to savanna, (2) nutrient additions in forest, ecotone, and savanna ecosystems, and (3) tillage practice and residue treatments in an agro-ecosystem. We used fractal dimensions nonlinear ($D_{non\text{-}lin}$) and linear (D_{lin}) based on number of aggregates (N) and mass of aggregates (M) (the range of values were 2.6−2.89 and 2.69−3.41, respectively) to capture the variations in the sizes of soil aggregates due to land use and treatments/management in these ecosystems. The variation in the values of non-linear fractal dimension based on mass ($D_{Mnon\text{-}lin}$) was smaller in forest and savanna ecosystems with and without nutrient additions, while the variation was wider in agro-ecosystems with different management practices. Linear fractal dimensions based on number (D_{Nlin}) and mass (D_{Mlin}) of aggregates varied marginally in these ecosystems and did not capture the variations in soil aggregates well. The variations in non-linear fractal dimension indicate that continued nitrogen loading in forest accelerates the formation of macro-aggregates, whereas in savanna the situation was reversed. The values of non-linear fractal dimensions did not show significant change after 6 years of nutrient additions in the ecotone; reflecting a buffering mechanism of this system in soil aggregate formation. On the basis of non-linear fractal dimension values, we conclude that residue retention and minimum tillage are appropriate for proper maintenance of soil aggregate stability for sustained crop production in the Indian dry land agro-ecosystems.

Keywords: soil aggregates; fractal; tillage practice; ecosystem; Indian dry tropics

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Introduction

Development of soil structure and aggregation is a dynamic property of soil that depends upon parent material, climate and management factors (Strudley et al. 2008). Soil aggregation has been reported as an important process controlling plant growth and carbon (C) sequestration (Blanco-Canqui and Lal 2004). Microaggregates (<0.3 mm) consist of separate particles, especially clay, that are often coated with fine inorganic and/or organic materials. In contrast, macro-aggregates (>0.3 mm) are the result of binding up of micro-aggregates (Elliott 1986). The ability of these soil aggregates to resist breakdown when soaked in water is important for maintaining permeability for supply of water and air to plant roots. The stability of soil aggregates varies due to agricultural management practices (Pirmoradian et al. 2005), land use, and nutrient inputs (Tripathi et al. 2008). Complexity is an intrinsic property of soil because of manifold feedbacks and multi-scale interactions. This creates significant difficulties for research, as no experimental sample, site or procedure is sufficient to fully represent the biogeochemical complexity of the natural medium, and thus accurate and efficient characterization of complex soil systems has become a prerequisite (Pachepsky et al. 2006).

Measurement of total soil aggregate stability with a single parameter is a difficult task because of the irregular shapes and sizes of aggregates. Fractal theory has been successfully used in assessing soil aggregate stability because of its scale-invariant property. Fractal theory has been used to describe soil hydrologic processes (Pachepsky et al. 2003; Martin et al. 2005; Pachepsky et al. 2000, Silvia et al. 2008). Gyldenkaerne and Jorgensen (2000) explained that soil measurements could be simplified in an ecological model by considering a scale (Yue et al. 2003). Many researchers have reported that soil aggregate stability (in

terms of mean weight diameter and the percentage by weight of different aggregates) is greater than that of soil aggregate in a given sieve-size because of lack of clear picture about the distribution of the aggregates in this approach (Puri et al. 1939). Thus, it is necessary to develop an index for describing the entire soil aggregate distribution with a single parameter by using sieve-size fractions. Many empirical indices have been proposed for describing the entire soil distribution with a single value (Perfect et al. 1991; Pirmoradian et al. 2005; Silvia et al. 2008).

The mean weight and geometric mean diameters have been used in describing soil aggregate-size distribution (Van Bavel 1949; Gardener 1956; Mazurak 1950). Baldock and Kay (1987) gave the following power function to describe the cumulative percentage of aggregates by weight with less than a characteristic linear dimension, x (that is equivalent diameter or height):

$$W_{<x} = Ax^{B} \quad (1)$$

where, W is the cumulative percentage weight of aggregate, x is the characteristic linear dimension and A, B are the regression coefficients. Coefficient B was used as an index of soil aggregate size distribution as it exhibited maximum variation.

The earlier indices were used to quantify soil aggregate size distribution as a result of sieve-size fractions. Fractal theory introduced scaling parameters; the fractal dimension has been found to be a more appropriate index for characterizing soil aggregate-size distribution. Mandelbrot (1982) has characterized fractals by power-law relations between the number and the size of objects. The value of the fractal dimension (D) is equal to the absolute value of exponent in the following relation:

$$N_{>x} = kx^{-D} \quad (2)$$

where, $N_{>x}$ is the cumulative number of objects greater than x, k is a constant equal to $N_{>x}$ at $x = 1$, and D is the fractal dimension. The value of D varies with the shape of individual objects within the distribution and the extent of aggregate fragmentation. The value of D increases with the increase in the aggregate fragmentation, showing the scale invariant property of D.

D exhibits a characteristic property of the number-size distribution of fragments as the mass of the material is broken down. The value of D has been used to characterize the size distribution of aggregates subsequent to fragmentation (Perfect and Kay 1991; Perfect et al. 1992). The value of D has also been found to capture the effect of soil properties and cropping patterns on the size distribution of aggregates as a result of fragmentation (Rasiah et al. 1992, 1993) with the value of $D > 3$. According to Tyler and Wheatcraft (1992) and McBratney (1993), the value of D calculated from mass-size distribution data should not be more than 3. However, Perfect et al. (1993) showed that values of $D > 3$ are theoretically possible, if the nature of the fragmentation process is multi-fractal (different regions of an object have different fractal properties). According to Rasiah and Biederbeck (1995), the value of D obtained using the non-linear fitting procedure was, in general, smaller.

Fractal parameters are sensitive to tillage treatments, such as mould-board ploughing increasing soil aggregate fragmentation in comparison with no-till (Perfect and Blevins 1997). Soil aggregate stability parameters like indirect number-size fractal dimension, mass-size fractal dimension, and mean weight diameter were compared by Sepashkhah et al. (2000). Use of fractal geometry in soil studies is gaining importance in recent years because of its scale invariance properties (Pachepsky et al. 2000; Martin et al. 2005; Pirmoradian et al. 2005; Chen et al. 2007).

The present study examines the sieve size fractions of soil particles through wet sieving method and calculates fractal dimension to demonstrate distribution changes in the sizes of soil aggregates in Indian tropical dry forests and its derived ecosystems under various treatment regimes. The application of fractal theory in quantifying changes in soil properties due to ecosystem perturbations is lacking in the Indian dry tropical region. In the present work, values of D calculated by non-linear and linear methods based on number and mass were compared with mean weight diameter and geometric mean diameter of the soil aggregates in these ecosystems. Further, the value of D was also correlated with important soil physico-chemical properties.

Materials and methods

Study sites and soil sampling

The data on changes in water stable soil aggregate for agro-ecosystem having different treatments were obtained from Kushwaha et al. (2001). Effects of six crop management practices including conventional tillage (CT), minimum tillage (MT), zero tillage (ZT) with residue (+R) and without residue (-R) on water-stable soil aggregates and organic carbon (C) were carried out during 1997-1998 at the dryland farm of the Institute of Agricultural Sciences, Banaras Hindu University, Varanasi. The experiment was designed to vary the degree of soil disturbance using different tillage and residue management practices (CT, MT and ZT with and without R). Malhotra et al. (1972) characterized the soil of this site as the Banaras type III (sand 31.7%, silt 64.8% and clay 3.5%). The details of the physical and chemical properties under various treatments are listed in Table 1. The data for soil particles after wet sieving in different treatments were obtained (Table 2) from Kushwaha et al. (2001).

The original data for forest, ecotone and savanna in this study were obtained from Tripathi et al. (2008) from Marihan range of East Mirzapur Forest Division in the Vindhyan plateau region. The soil was ultisol, reddish brown in colour and sandy loam in texture. Soil texture varied with different land uses like forest (sand 75%, silt 19% clay 6%), ecotone (sand 84%, silt 12% clay 3.6%) and savanna (sand 90%, silt 9.1%, clay 0.9%). The field work was to study the effect of nitrogen (N) and phosphorus (P) addition on forest, ecotone (degradation stage between forest and savanna), and savanna ecosystems (Tripathi et al. 2008). Permanent plots (100 m × 100 m) were marked in these ecosystems. Within each permanent plot, 9 sub-plots (each 12 m × 12 m) were demarcated for nutrient addition and soil sampling. N and P were added to the soil once each year (July/August) as urea (150

kg N· ha^{-1}· year^{-1}) and single super phosphate (50 kg P· ha^{-1}· year^{-1}), respectively, since 1994. Soils from these sub-plots were collected from the upper 10 cm layer in October 1999, after six years of annual N and P addition. From each sub-plot, soil samples were collected from 8 locations and pooled to make two samples per sub-plot. The details of the physical and chemical properties under various treatments in forest, ecotone, and savanna are listed in Table 3. The data for soil particles after wet sieving in different treatments (Table 4) were obtained from Tripathi et al. (2008). The soil bulk density (B_D, g· cm^{-3}) was measured using a steel sampling tube of known inner volume as described by Brady (1984).

Table 1. Soil physico-chemical properties in Indian agro-ecosystem under various treatments

Treatments	Replicate	Bulk Density (cm^{-3})	W_{HC} (mg· g^{-1})	Organic C (mg· g^{-1})	T_N (mg· g^{-1})	M_{BC} (mg· kg^{-1})	M_{BN} (mg· kg^{-1})
CT-R	1	1.279	413.0	8.10	0.90	251	25.1
	2	1.285	417.0	8.00	0.84	232	23.0
	3	1.262	408.0	7.40	0.87	223	23.6
	Mean±SE	1.27±0.006	412±2.6	7.8±0.21	0.87±0.017	235±8.3	23.9±0.6
CT+R	1	1.226	427.5	10.20	1.21	364	39.8
	2	1.246	420.8	9.80	1.17	343	38.6
	3	1.268	423.0	9.40	1.18	334	36.4
	Mean±SE	1.24±0.007	423±1.9	9.8±0.23	1.18±0.013	347±8.9	38.3±1.0
MT-R	1	1.310	422.0	8.55	0.93	281	28.8
	2	1.285	411.0	8.18	0.92	264	26.9
	3	1.289	416.0	7.98	0.91	269	27.4
	Mean±SE	1.29±0.007	416±3.2	8.2±0.15	0.92±0.006	271±5.1	27.7±0.6
MT+R	1	1.265	430.0	11.00	1.37	446	50.1
	2	1.245	431.0	11.45	1.32	406	45.1
	3	1.256	433.0	10.90	1.31	429	50.9
	Mean±SE	1.25±0.006	431±0.9	11.1±0.17	1.33±0.017	427±11.5	48.7±1.9
ZT-R	1	1.429	411.0	8.36	0.9	285	26.6
	2	1.418	409.0	8.16	0.89	294	25.8
	3	1.414	411.0	7.82	0.91	274	27.5
	Mean±SE	1.42±0.004	410±0.6	8.1±0.15	0.89±0.005	284±5.9	26.6±0.5
ZT+R	1	1.399	419.0	8.85	0.94	329	31.8
	2	1.402	410.0	8.35	1.01	310	29.6
	3	1.412	414.0	8.62	0.99	321	31.4
	Mean±SE	1.40±0.004	414±2.4	8.6±0.15	0.98±0.019	320±5.6	30.9±0.7

Notes: Treatment code: CT, MT and ZT represent conventional tillage, minimum tillage, and zero tillage respectively. –R and +R show residue removal and residue retention. W_{HC} is maximum water holding capacity. T_N is total nitrogen. M_{BC} and M_{BN} are the microbial biomass carbon and microbial biomass nitrogen respectively. (Data source: Kushwaha et al. 2001).

Table 2. Soil particle size distribution (mm) after wet sieving in different treatments in Indian agro-ecosystem

Treatment	Replicate	Soil particle size distribution (mm)					
		>4.75	2.0-4.75	0.5-2.0	0.3-0.5	0.053-0.3	<0.053
CT-R	1	14.2	9.0	13.5	9.3	42.8	19.7
	2	13.6	10.9	9.9	5.4	39.1	17.1
	3	12.2	7.3	11.6	7.3	39.9	17.8
	Mean±SE	13.3±0.6	9.0±1.1	11.6±1.0	7.3±1.1	40.6±1.1	18.2±0.8
CT+R	1	29.5	11.5	5.9	4.2	35.4	17.7
	2	25.4	9.9	9.3	5.9	32.6	15.9
	3	27.4	10.5	5.6	5.1	33.8	16.8
	Mean±SE	27.4±1.2	10.6±0.5	6.9±1.1	5.0±0.5	33.9±0.8	16.8±0.5
MT-R	1	21.2	7.8	10.4	11.5	39.7	15.9
	2	21.9	6.2	9.6	9.4	35.8	17.4
	3	19.0	5.9	10.2	8.8	36.2	14.6
	Mean±SE	20.7±0.9	6.6±0.7	10.0±0.2	9.9±0.8	37.2±1.2	15.9±0.9
MT+R	1	36.5	11.9	6.5	5.2	30.1	12.5
	2	34.2	11.4	5.8	6.8	28.9	11.8

Continue Table 2

Treatment	Replicate	Soil particle size distribution (mm)					
		>4.75	2.0-4.75	0.5-2.0	0.3-0.5	0.053-0.3	<0.053
	3	34.1	12.1	6.3	5.3	29.8	10.9
	Mean±SE	34.9±0.8	11.8±0.2	6.2±0.2	5.7±0.5	29.6±0.4	11.7±0.5
ZT-R	1	23.8	13.2	6.4	5.3	36.8	14.2
	2	22.7	11.3	8.4	7.8	34.5	18.4
	3	21.7	11.8	6.9	5.5	36.1	14.9
	Mean±SE	22.7±0.6	12.1±0.6	7.2±0.8	6.2±0.9	35.8±0.7	15.8±1.3
ZT+R	1	28.1	10.9	11.1	4.9	29.9	16.2
	2	27.5	13.3	8.9	5.1	31.6	13.4
	3	28.9	10.8	9.2	6.9	32.1	11.2
	Mean±SE	28.2±0.4	11.7±0.8	9.7±0.7	5.6±0.6	31.2±0.7	13.6±1.5

Notes: Treatment code: CT, MT and ZT represent conventional tillage, minimum tillage, and zero tillage respectively. –R and +R show residue removal and residue retention. (Data source: Kushwaha et al. 2001).

Table 3. Soil physico-chemical properties in Indian dry tropical forest, ecotone and savanna ecosystems under various treatments

Treatment		Replicate	Bulk density ($g\ cm^{-3}$)	W_{HC} ($mg\cdot g^{-1}$)	Organic C ($mg\ g^{-1}$)	T_N ($mg\cdot g^{-1}$)	M_{BC} ($mg\cdot kg^{-1}$)	M_{BN} ($mg\cdot kg^{-1}$)
Forest	Control	1	1.25	490	11.25	0.975	422	39.0
		2	1.30	476	9.51	0.902	384	45.0
		3	1.50	480	9.95	1.037	449	40.5
		Mean±SE	1.35±0.08	482±4	10.2±0.5	0.97±0.04	418±19	41.5±1.8
	N-added	1	1.30	500	13.25	1.293	552	84.5
		2	1.50	510	14.13	1.498	619	70.0
		3	1.40	520	12.22	1.316	605	74.0
		Mean±SE	1.4±0.06	510±6	13.2±0.6	1.37±0.06	592±20	76±4.3
	P-added	1	1.25	510	12.72	1.192	418	48.0
		2	1.35	480	11.25	1.018	454	50.0
		3	1.38	500	12.76	1.192	395	41.5
		Mean±SE	1.32±0.04	496±9	12.2±0.5	1.13±0.06	422±17	46.5±2.6
Ecotone	Control	1	1.55	425	7.66	0.838	318	36.9
		2	1.40	445	8.28	0.795	274	31.1
		3	1.30	430	9.08	0.739	342	28.8
		Mean±SE	1.41±0.07	433±6	8.3±0.4	0.79±0.03	311±20	32.2±2.4
	N-added	1	1.20	455	10.58	1.038	412	46.5
		2	1.35	465	11.96	1.198	471	55.5
		3	1.40	472	11.43	1.037	434	48.9
		Mean±SE	1.32±0.06	464±5	11.3±0.4	1.09±0.05	439±17	50.3±2.7
	P-added	1	1.45	410	9.128	0.848	320	29.4
		2	1.35	425	8.58	0.879	295	28.1
		3	1.24	432	8.36	0.780	307	31.5
		Mean±SE	1.34±0.06	422±7	8.7±0.2	0.83±0.03	307±7	29.6±1.0
Savanna	Control	1	1.25	390	5.83	0.572	215	17.8
		2	1.45	400	5.12	0.562	202	19.2
		3	1.55	374	6.21	0.638	179	19.7
		Mean±SE	1.42±0.09	388±8	5.7±0.3	0.59±0.02	198±10	18.9±0.6
	N-added	1	1.33	419	8.25	0.848	268	32.3
		2	1.20	440	7.16	0.788	270	35.4
		3	1.40	425	7.72	0.869	299	33.8
		Mean±SE	1.31±0.06	428±6	7.7±0.3	0.84±0.03	279±10	33.8±0.9
	P-added	1	1.50	390	7.24	0.731	218	22.0
		2	1.34	388	6.66	0.6449	190	20.6
		3	1.42	410	6.18	0.6686	204	22.9
		Mean±SE	1.42±0.05	396±7	6.7±0.3	0.68±0.03	204±8	21.8±0.7

Notes: W_{HC} is maximum water holding capacity. T_N is total nitrogen. M_{BC} and M_{BN} are the microbial biomass carbon and microbial biomass nitrogen respectively. Treatment code: C, N and P are control, nitrogen and phosphorus respectively. (Data source: Tripathi et al. 2008).

The soil particle-size data in Table 2 and 4 were obtained for six size fractions: > 4.75, 2, 0.5, 0.3, 0.053 and < 0.053 mm by the wet sieving method of Elliott (1986). After passing the soil sample through an 8-mm sieve, about 50 g of the soil was put on the first sieve and was gently moistened with water vapour to avoid sudden rupture of the soil aggregates. The set was then placed in water for 10 min and sieved for 50 strokes for a period of 2 min. Soil remaining on the sieves was then dried and weighed, and the weight ratio was calculated of the aggregates of each sieve to the total weight of the aggregates (Kushwaha et al. 2001; Tripathi et al. 2008).

Table 4. Soil particle size distribution after wet sieving in Indian tropical dry forest, ecotone and savanna under various treatments

Treatment		Replicate	Soil particle-size (mm)					
			>4.75	2.0-4.75	0.5-2.0	0.3-0.5	0.053-0.3	<0.053
Forest	Control	1	23.4	8.1	12.9	12.4	27.3	16.1
		2	22.3	7.3	14.9	10.8	29.8	15.2
		3	21	8.4	16.2	10.8	29.5	13.9
		Mean±SE	22.2±0.69	7.9±0.31	14.6±0.95	11.3±0.54	28.9±0.77	15.0±0.64
	N-added	1	23.5	13.1	12.9	13.3	26.4	10.9
		2	24.2	12.6	14.8	12.5	25.4	10.1
		3	25.3	13.8	14.2	14.1	25	9
		Mean±SE	24.3±0.51	13.1±0.35	13.9±0.56	13.3±0.46	25.6±0.42	10.0±0.54
	P-added	1	21.9	12	14.9	11.5	27	13.1
		2	22.1	11.5	15.1	12.9	24.9	13.7
		3	23.4	10.7	13.6	11.7	24.6	15.4
		Mean±SE	22.4±0.47	11.4±0.38	14.5±0.47	12.0±0.43	25.5±0.75	14.0±0.68
Ecotone	Control	1	12.7	11	14.5	12.9	40.7	17.7
		2	12.8	11.7	17	13.5	39	16
		3	13.9	10.9	14.4	11.7	37.1	16.4
		Mean±SE	13.1±0.38	11.2±0.25	15.3±0.85	12.7±0.52	38.9±1.00	16.7±0.51
	N-added	1	18.1	11.2	15.2	10.2	35.4	8.4
		2	16.4	12.1	16.1	10	33.2	10.4
		3	17.4	10.9	16.6	11	36.4	10.9
		Mean±SE	17.3±0.48	11.4±0.36	15.9±0.40	10.4±0.30	35.0±0.94	9.9±0.76
	P-added	1	16.1	11.5	16.5	9.4	31	15.2
		2	15.9	12.1	15	9.7	32.7	14.4
		3	17.3	11.2	16.5	8.8	31.9	14.5
		Mean±SE	16.4±0.43	11.6±0.27	16.0±0.50	9.3±0.27	31.9±0.48	14.7±0.26
Savanna	Control	1	11.7	18.1	7.8	4.7	41.7	14.3
		2	12.4	16.7	6.9	6.4	42.7	16
		3	13.1	16.9	8.2	5.9	43.5	12.9
		Mean±SE	12.4±0.41	17.2±0.44	7.6±0.38	5.7±0.50	42.6±0.51	14.4±0.87
	N-added	1	8.7	9.2	11.7	8.3	47.4	15.3
		2	9	8.7	11.5	7.1	48.1	16.7
		3	9.7	9.2	12.4	7.7	47	15.2
		Mean±SE	9.1±0.28	9.0±0.17	11.8±0.27	7.7±0.35	47.5±0.33	15.7±0.47
	P-added	1	10.4	16.2	7.3	5.7	44.1	15.9
		2	12.3	16.7	8.6	6	42.3	14.8
		3	11.5	16.9	9.4	6.1	40.5	14.1
		Mean±SE	11.4±0.54	16.6±0.20	8.4±0.61	5.9±0.12	42.3±1.04	14.9±0.51

Notes: Treatment code: C, N and P are control, nitrogen and phosphorus respectively. (Data source: Tripathi et al. 2008).

Calculation of soil mean weight diameter and geometric mean diameter

Mean weight diameter (M_{WD}) and geometric mean diameter (G_{MD}) were calculated using the equations reported by Perfect et al. (1992).

$$M_{\mathrm{WD}} = \frac{\sum_{i=1}^{n} (x_i w_i)}{\sum_{i=1}^{n} w_i} \tag{3}$$

$$G_{\mathrm{MD}} = Exp\left[\frac{\sum_{i=1}^{n} w_i \ln x_i}{\sum_{i=1}^{n} w_i}\right] \tag{4}$$

where x_i is the average diameter (mm) of the pore sizes of two consecutive sieves and w_i is the weight ratio of the aggregates remaining on the ith sieve.

The number of aggregates left on the ith sieve of a nest of sieves can be computed from the aggregate mass data as per Tyler and Wheatcraft (1992):

$$N(r < \overline{R}_n) \approx \sum_{i=1}^{n} N(R_i < r < R_{i+1}) = \sum_{i=1}^{n} \frac{M(R_i < r < R_{i+1})}{\frac{4}{3}\pi \overline{R}_i^3 \rho_p} \tag{5}$$

where, M ($R_i < r < R_{i+1}$) represents the mass of soil grains (g) between two consecutive sieve diameters (mm) and ρ_p is the grain density. Calculation of the aggregate number was based on the average size $\overline{R}$. Substituting Eq. (5) in Eq. (2) and assuming uniform particle density (Tyler and Wheatcraft 1992; Pirmoradian et al. 2005). The fractal dimension (*D)* from the mass size distribution was calculated as:

$$\sum_{x=1}^{x} \frac{M(x)}{x^3} = kx^{-D} \tag{6}$$

where, $M(x)$ is the total mass of aggregate of size less than x, k is a constant corresponding to the number of fragments of unit length and x is the characteristic linear dimension in mm.

The values of D calculated for the different sites and treatments were statistically analyzed using ANOVA (STATISTICA, StatSoft, USA). Tukey's honest significant difference test (HSD) was applied when significant differences ($p < 0.05$) between sites and treatments were detected.

Results

Soil physical and chemical properties

Soil bulk density (B_D) in agriculture soils varied from 1.24 g· cm^{-3} in conventional tillage (CT) to 1.42 g· cm^{-3} with zero tillage (ZT), (Table 1). The residue incorporation did not significantly affect maximum water holding capacity (W_{HC}) in agriculture soil. In the forest and derived ecosystems under study, soil B_D and W_{HC} ranged from 1.3 to 1.42 g· cm^{-3} and 422 to 510 mg· g^{-1}, respectively (Table 3). The effect of N addition on W_{HC} in natural and modified ecosystems was significant (p <0.05), whereas the effect of P was not significant. Soil organic C and total N (T_N) (mg· g^{-1}) varied significantly (p <0.05) in different ecosystems and treatments (Table 1, 3). Changes in the amount (mg· g^{-1}) of microbial biomass carbon (M_{BC}) and microbial biomass nitrogen (M_{BN}) were also significant (p <0.01) in various treatments and ecosystems and were closely related (R^2 = 0.92 for C and 0.78 for N) with the variations in the contents of the organic C and N.

Variations in fractal dimension due to changes in land use and nutrient additions

Mean values of non-linear fractal dimension based on mass ($D_{\text{Mnon-lin}}$) and number ($D_{\text{Nnon-lin}}$) were significantly affected by landscape transformation from forest to savanna, with and without N and P addition in these ecosystems with a few exceptions (Table 5). The value of fractal $D_{\text{Nnon-lin}}$ varied significantly (2.93 in savanna control and 3.29 in ecotone control plots). The value of $D_{\text{Mnon-lin}}$ varied narrowly from 3.2 in forest control to 3.26 in savanna and ecotone control plots. The values of non linear D based on mass ($D_{\text{Mnon-lin}}$) and number ($D_{\text{Nnon-lin}}$) decreased with N and P addition in these ecosystems except savanna in case of $D_{\text{Nnon-lin}}$. The values of linear fractal dimension based on number of aggregates (D_{Nlin}) and mass of aggregates (D_{Mlin}) were in the range of 2.68‒2.89 and 3.25‒3.35, respectively. The values of $D_{\text{N}lin}$ were generally lower than those of $D_{\text{Nnon-lin}}$. However, in the case of D based on mass of the aggregates *(*$D_{\text{Mnon-lin}}$), the reverse was recorded (Table 5). ANOVA showed significant (p < 0.05) differences between $D_{\text{Nnon-lin}}$ (F = 84 for ecosystems, 12.8 for treatments, and 65 for interactions of ecosystems and treatments) and $D_{\text{Mnon-lin}}$ (F = 38 for ecosystem, 19.4 for treatments, and 3.3 for interactions of ecosystems and treatments). ANOVA for D_{Nlin} (F = 118 for ecosystems, 17.2 for treatments, and 45 for interactions of ecosystems and treatments) and D_{Mlin} (F = 131 for ecosystems, 21.3 for treatments, and 4.3 for interactions of ecosystems and treatments) also revealed significant (p < 0.05) differences. The values of F were significantly different (P < 0.01); 489 (M_{WD}) and 126 (G_{MD}) for ecosystems, 7.9 (M_{WD}) and 13.2 (G_{MD}) for treatments, and 57 (M_{WD}) and 20 (G_{MD}) for interactions of ecosystems and treatments.

Table 5. Changes in non-linear and linear fractal dimensions

Ecosystem/ treatment		$D_{\text{Nnon-lin}}$	D_{Nlin}	$D_{\text{Mnon-lin}}$	D_{Mlin}	M_{WD}	G_{MD}
Forest	Control	3.24^{a}	2.78^{cf}	3.20^{ce}	3.30^{a}	1.96^{a}	0.54^{a}
	N-added	3.08^{b}	2.68^{a}	3.05^{a}	3.25^{b}	2.26^{b}	0.75^{b}
	P-added	3.14^{bd}	2.74^{bf}	3.11^{ba}	3.26^{b}	2.10^{b}	0.59^{a}
Ecotone	Control	3.29^{a}	2.84^{d}	3.26^{de}	3.35^{c}	1.52^{c}	0.43^{b}
	N-added	3.24^{ad}	2.73^{b}	3.21^{cd}	3.34^{c}	1.79^{d}	0.57^{a}
	P-added	3.23^{a}	2.79^{cd}	3.20^{dc}	3.33^{ca}	1.75^{d}	0.48^{a}
Savanna	Control	2.93^{c}	2.80^{cd}	3.26^{de}	3.35^{c}	1.57^{c}	0.42^{b}
	N-added	3.30^{a}	2.89^{e}	3.21^{dc}	3.34^{c}	1.14^{e}	0.31^{b}
	P-added	2.98^{c}	2.82^{d}	3.20^{dc}	3.33^{ca}	1.49^{c}	0.39^{b}

Notes: Different superscript letters in the columns show significant (p < 0.05) differences by Tukey's HSD. $D_{\text{Nnon-lin}}$ is non linear fractal dimension based on number of aggregates, D_{Nlin} is linear fractal dimension based on number of aggregates, $D_{\text{Mnon-lin}}$ is non linear fractal dimension based on mass of aggregates, D_{Mlin} is linear fractal dimension based on mass of aggregates, M_{WD} is mean weight diameter of aggregates and G_{MD} is geometric mean diameter of

aggregates.

Variations in fractal dimension due to tillage and residue treatments

The values of $D_{Nnon\text{-}lin}$ (2.63 to 3.16) and $D_{Mnon\text{-}lin}$ (2.8 to 3.2) varied significantly from ZT-R to CT-R in agro-ecosystem (Table 6). Residue retention significantly decreased with the values of $D_{Nnon\text{-}lin}$ and $D_{Mnon\text{-}lin}$ in CT and MT treatments. The values of $D_{Nnon\text{-}lin}$ and $D_{Mnon\text{-}lin}$ were not affected significantly in ZT treatment with and without residue retention. ANOVA showed significant ($p < 0.01$) differences between $D_{Nnon\text{-}lin}$ and D_{Nlin} (F = 15-41 for different treatments) and $D_{Mnon\text{-}lin}$ and D_{Mlin} (F = 42-81 for different treatments) in agro-ecosystems. The variations in the values of M_{WD} and G_{MD} were also significant (F = 154 and 5.5, p <0.05) in these treatments.

Relationship of fractal dimensions, M_{WD} and G_{MD} to quantify soil aggregate stability

Values of $D_{Nnon\text{-}lin}$, $D_{Mnon\text{-}lin}$, D_{Nlin}, D_{Mlin}, M_{WD} and G_{MD} for different ecosystems and treatments were pooled to examine correlations. $D_{Nnon\text{-}lin}$ and $D_{Mnon\text{-}lin}$ were correlated with D_{Nlin} and D_{Mlin} (Fig. 1 a and b), reflecting that the scaling factors based on counts were related to mass-based scaling factors by some equations. The slope and intercept of the regression lines were 1.35 and –0.66, respectively for number-based and 2.13 and –3.94 respectively for mass-based analysis, indicating a different value of D_{lin}. The values of D_{Nlin} ranged from 2.66-2.92, and those of $D_{Nnon\text{-}lin}$ from 2.63-3.38. However, the values of D_{Mlin} and $DM_{non\text{-}lin}$ varied between 3.22-3.41 and 2.66 -3.35, respectively, in these fitting procedures. The values of D were < 3 in most cases, whereas D was > 3 in some cases in both non-linear and linear methods.

Table 6. Changes in non-linear and linear fractal dimensions

Treat-ments	$D_{Nnon\text{-}lin}$	D_{Nlin}	$D_{Mnon\text{-}lin}$	D_{Mlin}	M_{WD}	G_{MD}
CT-R	3.16^{a}	2.83^{a}	3.20^{a}	3.41^{a}	1.40^{a}	0.35^{a}
CT+R	2.74^{be}	2.76^{b}	2.80^{be}	3.29^{b}	2.26^{b}	0.56^{a}
MT-R	3.10^{a}	2.82^{ab}	3.14^{a}	3.37^{c}	1.77^{c}	0.44^{a}
MT+R	2.63^{b}	2.67^{c}	2.69^{b}	3.23^{d}	2.78^{d}	0.70^{b}
ZT-R	2.78^{ce}	2.76^{b}	2.85^{ce}	3.31^{b}	2.04^{c}	0.51^{a}
ZT+R	2.81^{ce}	2.71^{cb}	2.89^{ce}	3.26^{bd}	2.39^{b}	0.67^{b}

Notes: Different superscript letters in the columns show significant ($p < 0.05$) differences by Tukey's HSD. $D_{Nnon\text{-}lin}$ is non linear fractal dimension based on number of aggregates, D_{Nlin} is linear fractal dimension based on number of aggregates, $D_{Mnon\text{-}lin}$ is non linear fractal dimension based on mass of aggregates, D_{Mlin} is linear fractal dimension based on mass of aggregates, M_{WD} is mean weight diameter of aggregates and G_{MD} is geometric mean diameter of aggregates. Treatment code: CT, MT and ZT represent conventional tillage, minimum tillage, and zero tillage respectively. –R and +R show residue removal and residue retention..

M_{WD} and G_{MD} were significantly negatively correlated (R^2 = 0.1-0.34, p <0.05) with the values of $D_{Nnon\text{-}lin}$ and $D_{Mnon\text{-}lin}$. G_{MD} and M_{WD} separately accounted for 34% and 9% variability, respectively, in the values of $D_{Nnon\text{-}lin}$ (Fig. 1 c and d).

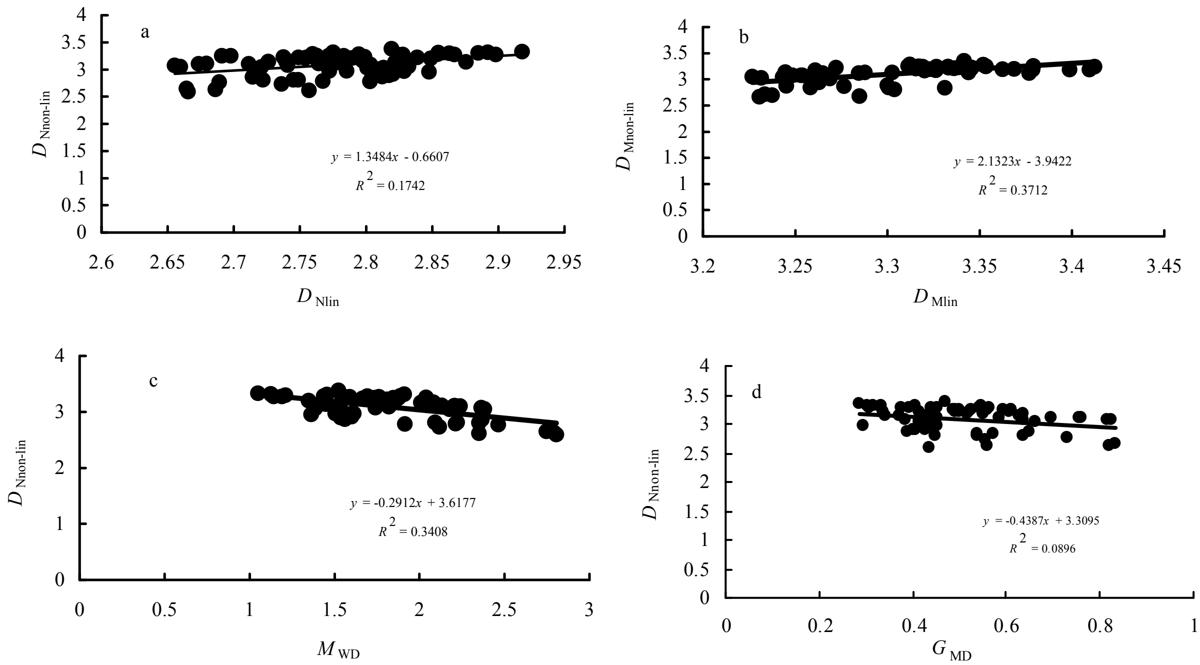

Fig. 1 Fractal dimensions of soil aggregates. (a) Number based non-linear fractal dimension ($D_{Nnon\text{-}lin}$) versus number based linear fractal dimension (D_{Nlin}) ; (b) mass based non-linear fractal dimension ($D_{Mnon\text{-}lin}$) versus mass based linear fractal dimension (D_{Mlin}) ; (c) number based non-linear fractal dimension ($D_{Nnon\text{-}lin}$) versus mean weight diameter (M_{WD}); (d) number based non-linear fractal dimension ($D_{Nnon\text{-}lin}$) versus geometric mean diameter (G_{MD}). All correlation coefficient values are significant at p < 0.05.

Relationship of soil physico-chemical properties with D and soil aggregate stability

All indices for depicting the soil aggregate size distribution were examined for correlation with soil physico-chemical properties (Tables 1, 3). $D_{\mathrm{Nnon\text{-}lin}}$ was not significantly correlated with any physico-chemical properties. However, the $D_{\mathrm{Mnon\text{-}lin}}$ was significantly negatively correlated (r = 0.64, p < 0.05) with T_{N}. D_{Nlin} and D_{Mlin} were significantly negatively correlated (r = 0.66 – -0.79, p <0.05) with soil organic C and T_{N}. T_{N} was also significantly negatively correlated (r = 0.66, p <0.05) with M_{WD} and G_{MD}.

To evaluate the effect of different soil physico-chemical properties on the values of D, we regressed the values of $D_{\mathrm{Nnon\text{-}lin}}$, $D_{\mathrm{Mnon\text{-}lin}}$, D_{Nlin} and D_{Mlin} with soil properties. Multiple regression analysis suggested that W_{HC}, T_{N}, and B_{D} were better predictors of D, accounting for 75% and 85% variability in $D_{\mathrm{Nnon\text{-}lin}}$ and $D_{\mathrm{Mnon\text{-}lin}}$, respectively. The equations were as follows:

$$D_{\mathrm{Nnon\text{-}lin}} = 3.184 + 0.007\,(W_{\mathrm{HC}}) - 1.16\,(T_{\mathrm{N}}) - 1.42\,(B_{\mathrm{D}})$$
$$R^2 = 0.75,\ p < 0.01 \tag{7}$$

$$D_{\mathrm{Mnon\text{-}lin}} = 4.23 - 1.45\,(T_{\mathrm{N}}) + 0.003\,(W_{\mathrm{HC}}) - 1.055\,(B_{\mathrm{D}}),$$
$$R^2 = 0.85,\ p < 0.01 \tag{8}$$

where, T_{N} is total N (mg· g^{-1}).

Discussion

The values of D_{Nlin} and D_{Mlin} were always greater than those of $D_{\mathrm{Nnon\text{-}lin}}$ and $D_{\mathrm{Mnon\text{-}lin}}$, whereas the standard errors in D_{Nlin} and D_{Mlin} were lower than those of $D_{\mathrm{Nnon\text{-}lin}}$ and $D_{\mathrm{Mnon\text{-}lin}}$. Other investigators (Rasiah et al. 1995; Perfect et al. 1994; Rasiah and Biederbeck 1995; Pirmoradian et al. 2005) reported similar results by using detailed error analysis. In the present study, the values of $D_{\mathrm{Nnon\text{-}lin}}$ and $D_{\mathrm{Mnon\text{-}lin}}$ were more reliable than that of values of D_{Nlin} and D_{Mlin} to account for differences in landscape change, nutrient addition, and management regimes in agro-ecosystems. Rasiah et al. (1995) also showed that the values of non linear D were more reliable than those of linear D for soil aggregate fragmentation. Smith et al. (1980) reported that during the log-transformations, smaller values are weighted more heavily than the larger values. Therefore, when log-transformation was used in the fitting procedure (as in the case of linear method), considerably more emphasis was placed on the values of N_i corresponding to the larger values of x_i. During the process of log-transformation of the raw data, the error in the data was also log-transformed (Gold 1977). In contrast, when the raw data (without log-transformation) were used for fitting in the case of $D_{\mathrm{Nnon\text{-}lin}}$ and $D_{\mathrm{Mnon\text{-}lin}}$, the estimates were not biased towards any size class, compared with the linear fitting procedure. The linear D and non linear D based on mass and number were significantly positively correlated with each other in the present study. However, the values of $D_{\mathrm{Nnon\text{-}lin}}$ and $D_{\mathrm{Mnon\text{-}lin}}$ more strongly reflected changes due to landscape transformation, nutrient enrichment, tillage, and residue management in agro-ecosystems.

Higher values of $D_{\mathrm{Nnon\text{-}lin}}$ and $D_{\mathrm{Mnon\text{-}lin}}$ corresponding to more fragmentation of soil aggregates are acceptable in terms of theories of soil physics (Perfect and Kay 1991; Pirmoradian et al. 2005). Tyler and Wheatcraft (1992) argued that the value of D should not be more than 3 in physically possible situations. Values of $D_{\mathrm{Nnon\text{-}lin}}$ were significantly higher in control plots (3.24–3.29) in forest and ecotone, and lower in savanna (2.9). Nitrogen loading decreased the value of $D_{\mathrm{Nnon\text{-}lin}}$ (3.08) compared to control plots in the forest ecosystem, but increased its value in savanna (3.3). The increased D indicated that the fractal size distribution was dominated by a large number of micro-aggregates. This trend indicates the possibility that N loading may cause varying responses in forest and savanna ecosystems in dry tropics with respect to soil aggregation. In general, according to aggregate hierarchy theory, the entanglement of particles within hyphae networks is a major factor for the formation of macro-aggregates (Oades and Waters 1991; Tisdale et al. 1997), whereas the production of mucilage by bacteria and fungi enhances the formation of microaggregates (Oades 1993). Addition of exogenous N to the soil has been reported to enhance litter decomposition in a variety of tropical and temperate ecosystems (Kuperman 1999; Mo et al. 2006). In general, significant negative correlation of D_{Nlin} and D_{Mlin} with M_{BC} and M_{BN} and positive correlation with M_{WD} and G_{MD} showed that the increased microbial biomass enhances macro-aggregation in the soil. Increased M_{BN} may accelerate the binding of micro-aggregates into macro-aggregates in forest soils as a result of tight cycling of nutrients in well-developed soil micro-flora. In the savanna ecosystem, weak micro-floral development due to fragile nutrient cycling might speed up the breaking of macro-aggregates into micro-aggregates after N input (Tripathi et al. 2008). Major soil physico-chemical properties have been found to affect water-stable soil aggregates (Barthes et al. 2008).

Perfect and Blevins (1997) suggested that the fractal parameter can be used to characterize both soil aggregation and fragmentation and this parameter is also sensitive to tillage management. Pirmoradian et al. (2005) recommended that tillage-planting and no- or zero-tillage are most efficient in maintaining soil aggregate stability. In the present study, agro-ecosystems were characterized by decreased values of $D_{\mathrm{Nnon\text{-}lin}}$ in CT-R, compared to ZT-R.

Perfect et al. (2004) reported a significant difference in the values of $D_{\mathrm{Mnon\text{-}lin}}$ for tillage treatment, with smaller values in zero-tillage, compared to plough-disced treatment. Pirmoradian et al. (2005) reported a lower range of variation in $D_{\mathrm{Mnon\text{-}lin}}$ (2.948–2.963), $D_{\mathrm{Nnon\text{-}lin}}$ (2.028–2.298) for different tillage treatments. In our study, the $D_{\mathrm{Mnon\text{-}lin}}$ and $D_{\mathrm{Nnon\text{-}lin}}$ varied widely within the ecosystem and treatments and correlated with each other (Perfect et al. 1992). Thus, we recommend both of these measurements of $D_{\mathrm{Mnon\text{-}lin}}$ and $D_{\mathrm{Nnon\text{-}lin}}$ for this region. Variations in the D_{Nlin}, D_{Mlin} and G_{MD} values were small and so these are not suggested for this kind of ecosystems. The variation in M_{WD} was greater than for D_{Nlin}, D_{Mlin} and G_{MD} but negatively correlated

with $D_{\mathrm{Mnon\text{-}lin}}$ and $D_{\mathrm{Nnon\text{-}lin}}$, depicting soil aggregate formation. Pirmoradian et al. (2005) reported positive correlation between M_{WD} and $D_{\mathrm{Nnon\text{-}lin}}$, whereas we recorded negative correlation between M_{WD} and $D_{\mathrm{Nnon\text{-}lin}}$. Negative correlation between M_{WD} and $D_{\mathrm{Nnon\text{-}lin}}$ in our case is more logical, because theoretically M_{WD} increases with macro-aggregation, whereas higher values of D indicate micro-aggregation.

Conclusion

The values of $D_{\mathrm{Nnon\text{-}lin}}$ and $D_{\mathrm{Mnon\text{-}lin}}$ for soil aggregate stability are sensitive to changes, compared with $D_{\mathrm{N}lin}$ and D_{Mlin} for this region due to management practices in agro-ecosystems and nutrient addition in natural and modified ecosystems. On the basis of the values of D, residue retention and minimum tillage are recommended for the Indian dry land agro-ecosystems. In addition, the values of D suggest that the global change process, particularly N loading, might accelerate the formation of macro-aggregates in the forests and micro-aggregates in the savanna ecosystems. The values of D were not affected significantly due to nutrient addition over six years in the ecotone, reflecting the strong buffering capacity of ecotone with respect to soil aggregate formation. Further studies are needed to corroborate these findings by multiple aggregate measurements over longer time periods.

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